

# APPLICATION OF PASSIVE POLARIMETRIC RADIOMETRY TO REMOTE SENSING OF OCEAN WIND DIRECTION , INTERNAL WAVES, AND FOAM

## Final Progress Report

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This report summarizes the results from a program of study for advanced undergraduate and graduate training in ocean remote sensing science and engineering at the Georgia Institute of Technology. The goals of the program were (1) to improve the state of understanding of ocean surface microwave thermal emission and (2) to develop new techniques for passive microwave spaceborne and airborne remote sensing of ocean surface parameters. The program was focussed on measurement of ocean surface wind direction by purely passive means, including the use of the third Stokes' parameter for wind direction measurement. The sensitivity of microwave observations to other variables of sea state, including the effects of maritime convection, was also studied.

The program involved the collection and analysis of data using a unique four-band imaging radiometer, the Polarimetric Scanning Radiometer (PSR), developed by Georgia Tech and later upgraded by the NOAA Environmental Technology Laboratory [6,7]. The PSR is a tri-polarimetric airborne imaging radiometer designed for imaging of the first three Stokes' parameters ( $T_v$ ,  $T_h$ ,  $T_u$ ) at several key microwave window frequencies, including 10, 18.7, 37, and 89 GHz.<sup>2</sup> Measurement of the third Stokes parameter was accomplished using an innovative three-level digital correlator, designed specifically for the PSR instrument [5]. Development of the PSR was initially supported under a parent grant from the U.S. Office of Naval Research.<sup>3</sup> The PSR was first operated on the NASA P-3B during the Labrador Sea Deep Convection Experiment<sup>4</sup> in March, 1997 [1,8].

The focus of the research has been to develop algorithms and aircraft and satellite remote sensing systems for imaging of ocean surface winds using passive microwave radiometers. The application of passive radiometry to ocean surface imaging, specifically using polarimetric microwave measurements of the third and fourth Stokes' parameters,

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2. A detailed description of the PSR can be found on the world wide web at <http://www1.etl.noaa.gov/radiom/psr.html>.

3. ONR grant # N0014-98-F-0071 for Airborne Measurements of Oceanic Wind Vector Fields Over the Labrador Sea Using Passive Polarimetric Radiometry.

4. A description of the Labrador Sea P-3 experiment can be found in reference [1], and a description of the PSR and copy of reference [1] can be found at <http://www1.etl.noaa.gov/radiom/psr.html>.

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has been identified as a potentially useful and low-cost means of obtaining the magnitude and direction of near-surface ocean winds from space. Two major results of this work have been the empirical characterization of polarimetric thermal emission signature from a wind-driven ocean surface using airborne measurements and the development of a maximum likelihood wind vector retrieval algorithm suitable for the retrieval of aircraft or satellite wind vector fields. A related result has been the characterization of the effects of maritime convection on the polarimetric surface emission signature.

Questions to be answered using the PSR Labrador Sea data included: (1) What are the frequency and wind-speed dependencies of the observed azimuthal harmonic signatures? (2) What are the relative impacts of foam, wave asymmetry, and resonant thermal emission on the wind signatures? (3) What are the impacts on the azimuthal harmonic signatures caused by clouds and water vapor? (4) What is the impact of fetch and stability on the azimuthal signatures? (5) Do the wind signatures observed from aircraft correlate with those observed from the SSM/I instrument? (6) What is the utility of a two-look (fore and aft) method for determining the wind vector at a given pixel?

The PSR aircraft data from the Labrador Sea Experiment required several levels of processing before the data could be interpreted as absolute calibrated brightness temperatures. Accordingly, a general purpose processing system was written in Matlab to perform the following functions: (1) merge and resample the various raw data streams of significance, including radiometric counts, scanhead angle position, calibration load temperature, and aircraft attitude, (2) calibrate the data using both sky looks (obtained during steep aircraft rolls) and periodic looks at hot and ambient blackbody targets. A unique nonlinear Wiener filter calibration algorithm was tailored for this process, (3) account for the effects of the nonlinear relationship between the digital correlation signal and  $T_U$ , (4) correct for antenna beam angle variations and polarization basis rotation caused by small aircraft rolls and pitches, and (5) correct for scan bias resulting from systematic variations in slipstream-induced vibration as a function of scan angle. The above processing was performed on all Labrador Sea PSR data, and the data was subsequently analyzed for wind-related azimuthal harmonic variations.

The above-described data processing steps resulted in approximately 25 hours of calibrated brightness imagery with an absolute error (i.e., bias) of less than 3-10 K (depending on channel) and with a typical radiometric resolution ( $\Delta T_{rms}$ ) of 1-2.5 K per 25-msec sample. Data during several Labrador Sea hex-cross maneuvers have been used to corroborate the azimuthal wind direction harmonics observed using the SSM/I instrument, with excellent agreement being obtained (Figure 1) for 12-15 m/sec wind speeds [9]. The measured azimuthal harmonic amplitudes were also analyzed for wind speed dependence (Figure 2), with reasonable agreement obtained between the PSR and SSM/I data.

The agreement between the PSR Labrador Sea azimuthal harmonics for wind speeds in the 12-15 m/sec range is excellent for the frequencies and polarizations available from SSM/I wind vector studies (37 GHz, v and h). The first harmonic is dominant in the  $T_v$  data, and the second is dominant in the  $T_h$  data. The  $T_U$  data is comprised of both first and second harmonics of significant strength although the relative strength of the second harmonic is greater at 10 GHz than at 37 GHz. Overall the data suggest a small variation of harmonic amplitude with frequency, the amplitudes being ~10-50% higher (depending on polarization) at 37 GHz than at 10 GHz. Nonetheless, the 10 GHz signals appear to be reasonably strong with respect to typical radiometric precisions and thus useful for wind direction sensing. The 10 GHz harmonic amplitudes – especially  $T_v$  – also appear to be

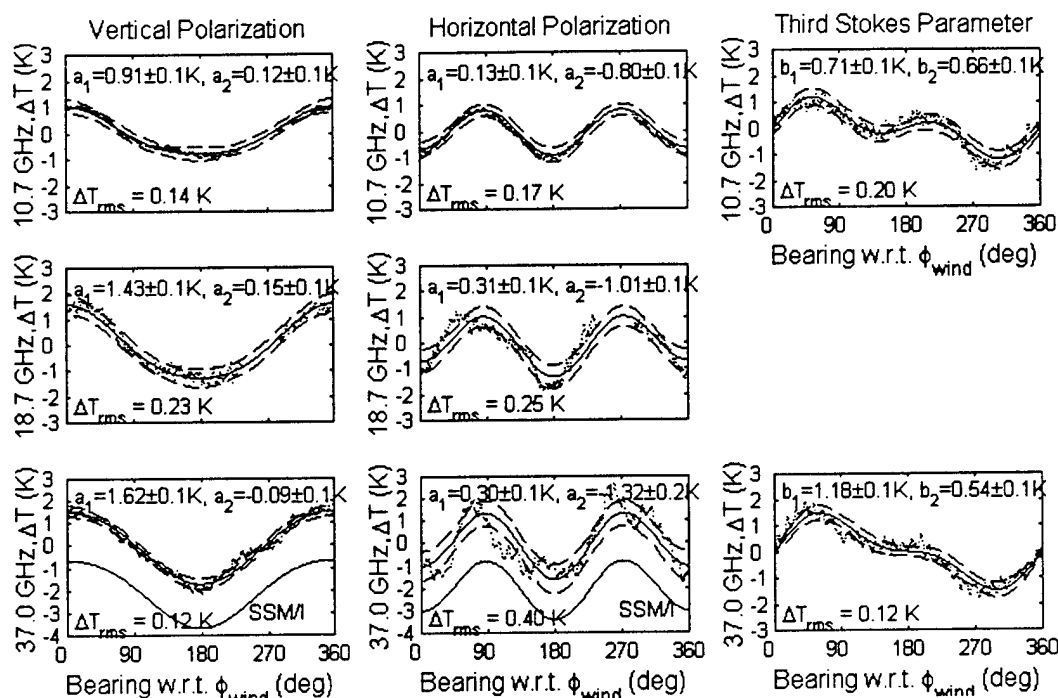


Figure 1. Wind vector azimuthal harmonics during hex-cross maneuvers on March 4, 1997 over the R.V. Knorr during the Labrador Sea Deep Convection experiment. The SSM/I harmonics for 37 GHz v & h polarizations are shown displaced by  $-2$  K for comparison.

increasing with wind speed at the high range of the data (20 m/sec) while the higher frequency harmonics tend to exhibit amplitude saturation at that wind speed. The result suggests an increased utility of the 10.7 GHz data in high wind speed conditions. Finally, it is noted that the  $T_U$  harmonic amplitudes appear to be consistent with calculations based upon an asymmetric wave model of the ocean surface [ref. 2, p. 153].

It was also found (not illustrated) that the  $T_U$  data are significantly less affected by the presence of clouds and convection than  $T_v$  or  $T_h$ . It is hypothesized that clouds and/or local hydrodynamic modulation caused by inhomogeneities in the marine boundary layer momentum fluxes at meso-beta spatial scales ( $\sim 10$  km) can significantly perturb  $T_v$  and  $T_h$  harmonic measurements, but much less so for  $T_U$  [3,7].

## IMPACT/APPLICATIONS

The development of the PSR airborne conical scanning radiometer system and its operation during the Labrador Sea campaign have proven the utility of airborne passive microwave wind vector sensing for high-resolution ocean surface studies. The Labrador Sea data have provided independent corroboration of the SSM/I harmonics amplitudes observed from satellite and a geophysical model function for use in the design of the WindSAT and NPOESS CMISS satellite wind vector sensors. The data extend the SSM/I geophysical model function for wind vector harmonic amplitudes to the important bands down to 10 GHz and the third Stokes' parameter. The impact of clouds and local

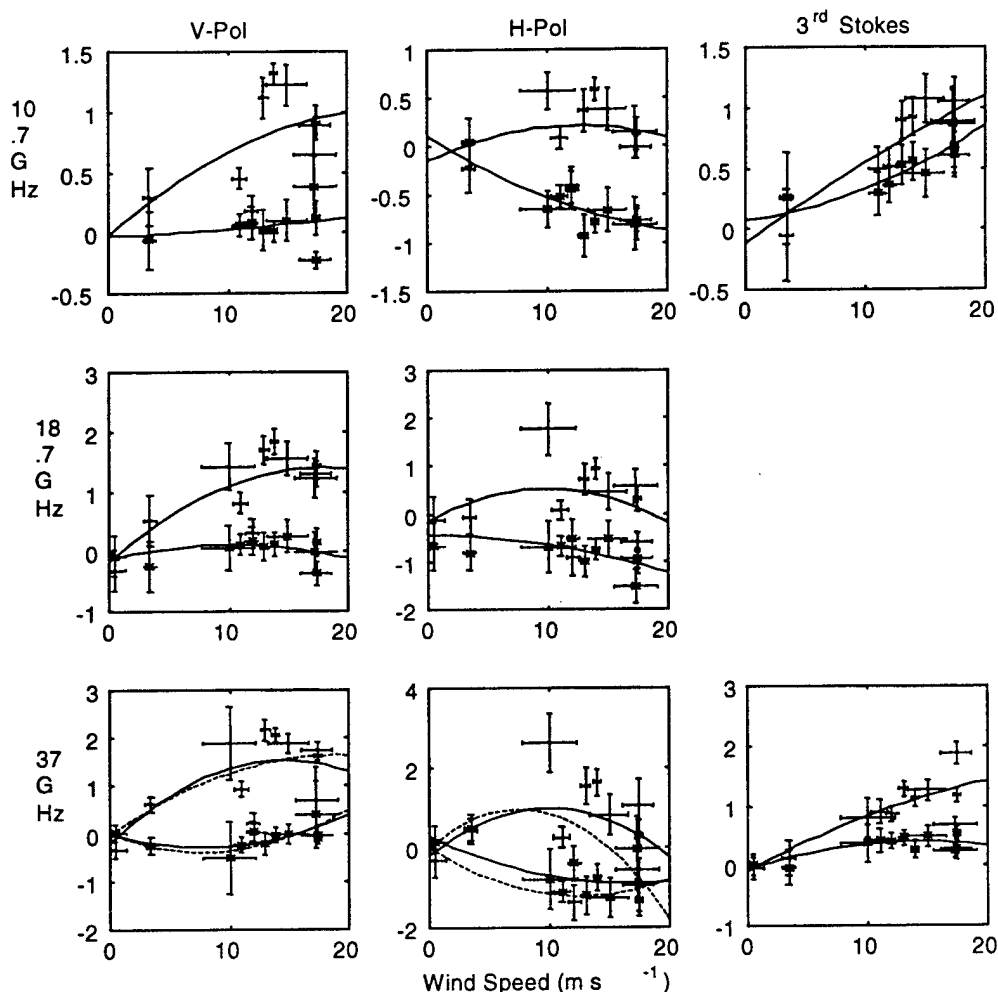


Figure 2. Wind direction harmonic amplitudes obtained from hex cross maneuvers during the Labrador Sea Deep Convection experiment: first harmonic (•) and second harmonic (★). The SSM/I harmonic amplitude coefficients for 37 GHz v and h polarizations are shown as dashed lines for comparison.

convection on the PSR data suggest that the polarization channels  $T_U$  and  $T_V$  will be relatively immune to the effects of clouds and convection, but that frequencies as low as even 10 GHz may be significantly affected, particularly on meso-beta spatial scales and during unstable conditions.

#### STUDENT SUPPORTED UNDER THIS ASSERT GRANT

(1) Jeffrey R. Piepmeier, Ph.D. Candidate, Electrical Engineering, Georgia Institute of Technology. Ph.D. thesis proposal "Polarimetric Microwave Radiometry for Remote Sensing of Ocean Surface Winds," accepted July 1997. Expected graduation date: Summer 1999. Mr. Piepmeier won third place in 1998 IGARSS Student Paper Prize Competition for work pertaining to the Labrador Sea Experiment.

(2) Dr. Marián Klein, Ph.D (Electrical Engineering, Technical University of Košice, Slovak Republic) Fulbright Postdoctoral Scholar, October 1996-August 1998.

(3) Christopher D. Campbell, undergraduate research assistant, Summer 1995-Winter 1996. B.S., Aerospace Engineering, Winter 1990. B.S., Electrical Engineering, Winter

1996. Currently: Electronics engineer, Scientific Atlanta, Atlanta, GA, Spring 1996-present.

(4) Paul Lowe, GIT Supreem (Summer Program for Electrical Engineering Minorities), Summer 1997. Currently: Undergraduate student in physics at the University of Maryland at Baltimore County, MD.

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[9] Piepmeier, J.R., A.J. Gasiewski, M. Klein, V. Bohm, and R.C. Lum, "Ocean Surface Wind Direction Measurement by Scanning Microwave Polarimetric Radiometry, Proceedings of the 1998 International Geoscience and Remote Sensing Symposium, pp. 2307-2310, presented in Seattle, WA, July 6-10, 1998.

In addition to the above, three journal publications (based on [3,5,9]), and one Ph.D. thesis are in preparation.